Future long baseline neutrino experiments

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based on

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Outline

- Status quo
- Neutrino oscillation
- Experimental strategies
  - T2KK
  - NOνA*
  - WBB
- Comparison & robustness
- Summary

Status quo

- Conversion of ν_e from the Sun into $\nu_\mu + \nu_\tau$
- Disappearance of $\bar{\nu}_e$ from nuclear reactors at a distance of $\sim 200\,\mathrm{km}$
- Disappearance of ν_μ from the Atmosphere
- Disappearance of ν_μ from a neutrino beam
- No disappearance of $\bar{\nu}_e$ from nuclear reactors at a distance of $\sim 1\,\mathrm{km}$
- No disappearance of ν_μ from high energy beams at a distance of $\sim 0.5\,\mathrm{km}$
- No appearance of ν_e at MiniBooNE

Status quo

A common framework for all the neutrino data is oscillation.

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \lesssim 0.15$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2.5 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.05\,\mathrm{eV}$$

but we currently do not know which neutrino is the heaviest.

Status quo

Quarks

$$U_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

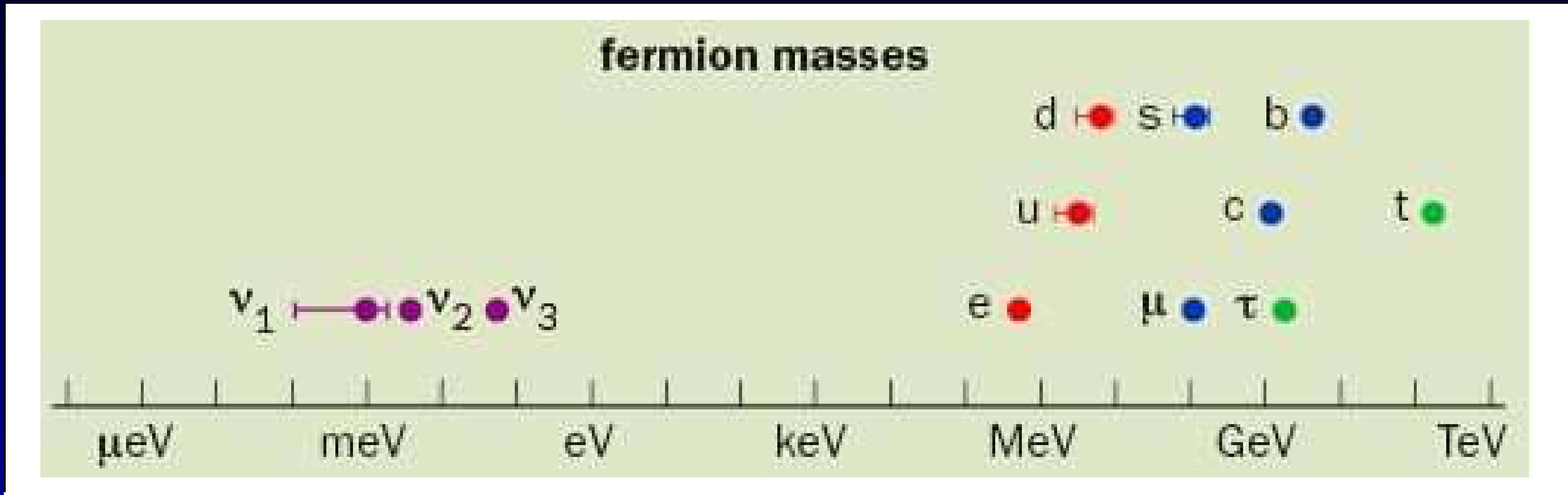
Neutrinos

$$U_\nu = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

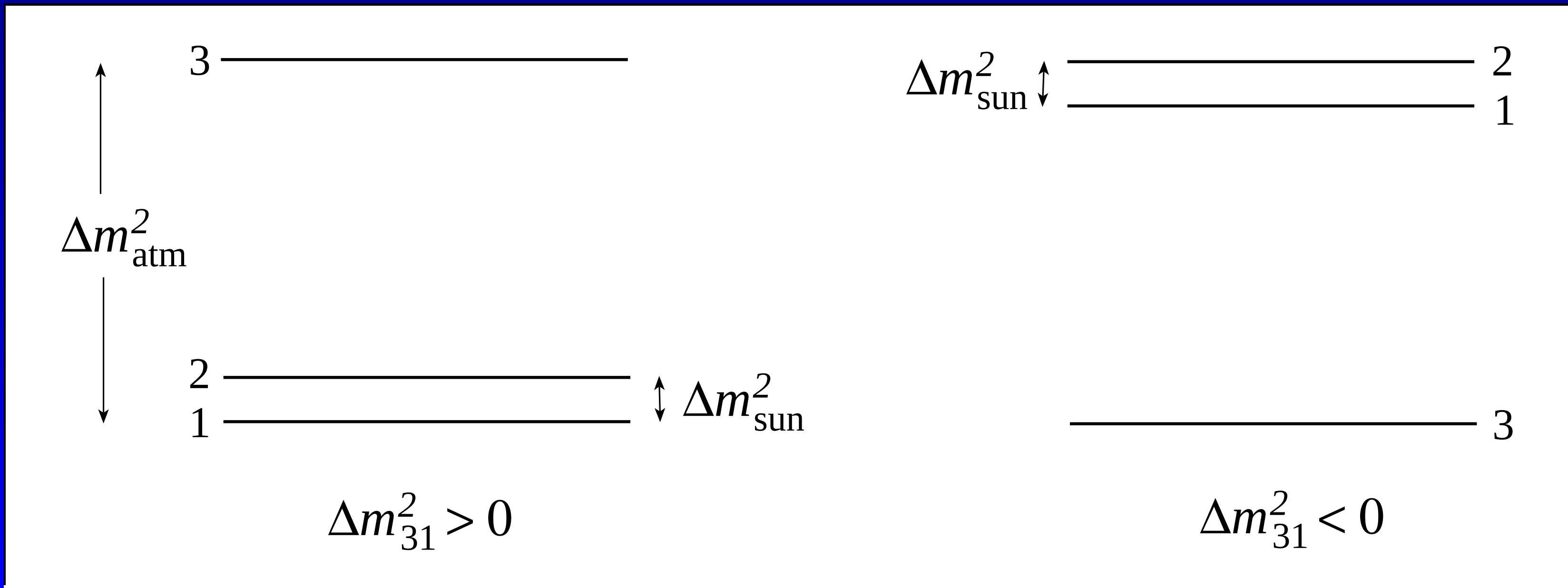
Why are neutrino mixings so large?

Status quo

Mass hierarchy in the SM



What makes neutrinos so much lighter?



Status quo

Neutrinos in the Standard Model (SM) are strictly massless, *ie.* there is no way to write a mass term for neutrinos with only SM fields which is gauge invariant and renormalizable.

Neutrinos are massive in reality – thus neutrino mass requires physics beyond the standard model.

Neutrino oscillations

The mass eigenstates are related to flavor eigenstates by U_ν, thus a neutrino which is produced as flavor eigenstate is a superposition of mass eigenstates. These mass eigenstates propagate with different velocity and a phase difference is generated. This phase difference gives rise to a finite transition probability

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{ij} U_{\alpha j} U^*_{\beta j} U^*_{\alpha i} U_{\beta i} e^{-i \frac{\Delta m^2_{ij} L}{2E}} \sim \sin^2 2\theta \sin^2 \frac{\Delta m^2_{ij} L}{4E}$$

Neutrino oscillation is a quantum mechanical interference phenomenon and therefore it is uniquely sensitive to extremely tiny effects.

Neutrino oscillations – CP viol.

Like in the quark sector mixing can cause CP violation

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

The size of this effect is proportional to

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta$$

The experimentally most suitable transition to study CP violation is $\nu_e \leftrightarrow \nu_\mu$, which is only available in beam experiments.

Neutrino oscillation – matter

The charged current interaction of ν_e with the electrons creates a potential for ν_e

$$A = \pm 2\sqrt{2} G_F \cdot E \cdot n_e$$

where $+$ is for ν and $-$ for $\bar{\nu}$.
This potential gives rise to an additional phase for ν_e and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.

Neutrino oscillation – matter

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

$$\Delta m^2 \simeq A$$

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

$P(\nu_\mu \to \nu_e)$

Two-neutrino limit – $\Delta m^2_{21} = 0$

$$\approx \sin^2 2\theta_{13} \quad \sin^2\theta_{23} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

with $\hat{A} = \frac{2\sqrt{2} G_F\, n_e\, E}{\Delta m^2_{31}}$ and $\Delta = \frac{\Delta m^2_{31}\, L}{4E}$

$P(\nu_\mu \to \nu_e)$

Three flavors – $\Delta m^2_{21} \neq 0$

$$
\begin{aligned}
&\approx \quad \sin^2 2\theta_{13} \quad \sin^2\theta_{23} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2} \\
&\pm \quad \alpha \sin 2\theta_{13} \quad \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
&+ \quad \alpha \sin 2\theta_{13} \quad \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
&+ \quad \alpha^2 \quad \cos^2\theta_{23}\sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

with $\hat{A} = \frac{2\sqrt{2} G_F\, n_e\, E}{\Delta m^2_{31}}$ and $\Delta = \frac{\Delta m^2_{31}\, L}{4E}$

$P(\nu_\mu \to \nu_e)$

Small quantities – $\alpha := \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$

$$\approx \quad \sin^2 2\theta_{13} \quad \sin^2\theta_{23} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

$$\pm \quad \alpha \sin 2\theta_{13} \quad \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha \sin 2\theta_{13} \quad \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha^2 \quad \cos^2\theta_{23}\sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

with $\hat{A} = \frac{2\sqrt{2}G_F\, n_e\, E}{\Delta m^2_{31}}$ and $\Delta = \frac{\Delta m^2_{31}\, L}{4E}$

Eight-fold degeneracy

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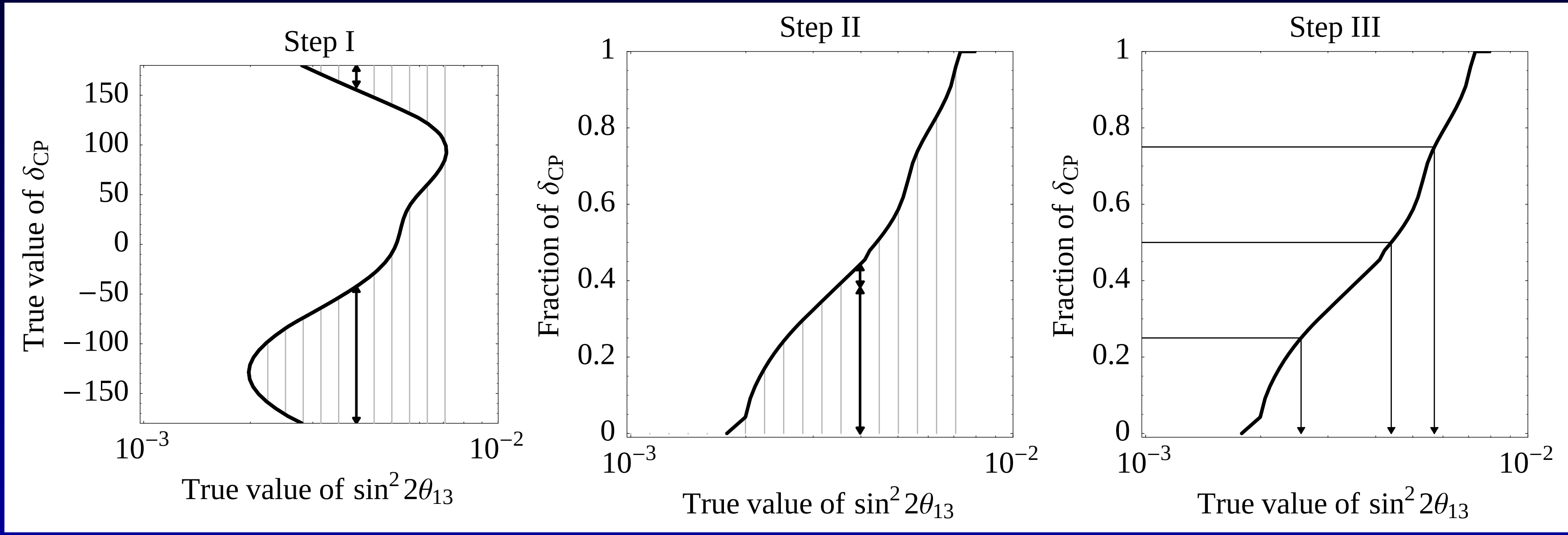
- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow$ $\mathcal{T}_t := \theta_{23} \rightarrow \pi/2 - \theta_{23}$
- Both transformations $\mathcal{T}_{st} := \mathcal{T}_s \oplus \mathcal{T}_t$

CP fraction



- reduces 2D plot to 3 points
- allows unbiased comparison
- allows risk assessment
- CPF = 1, worst case – guaranteed sensitivity
- CPF =0, best case

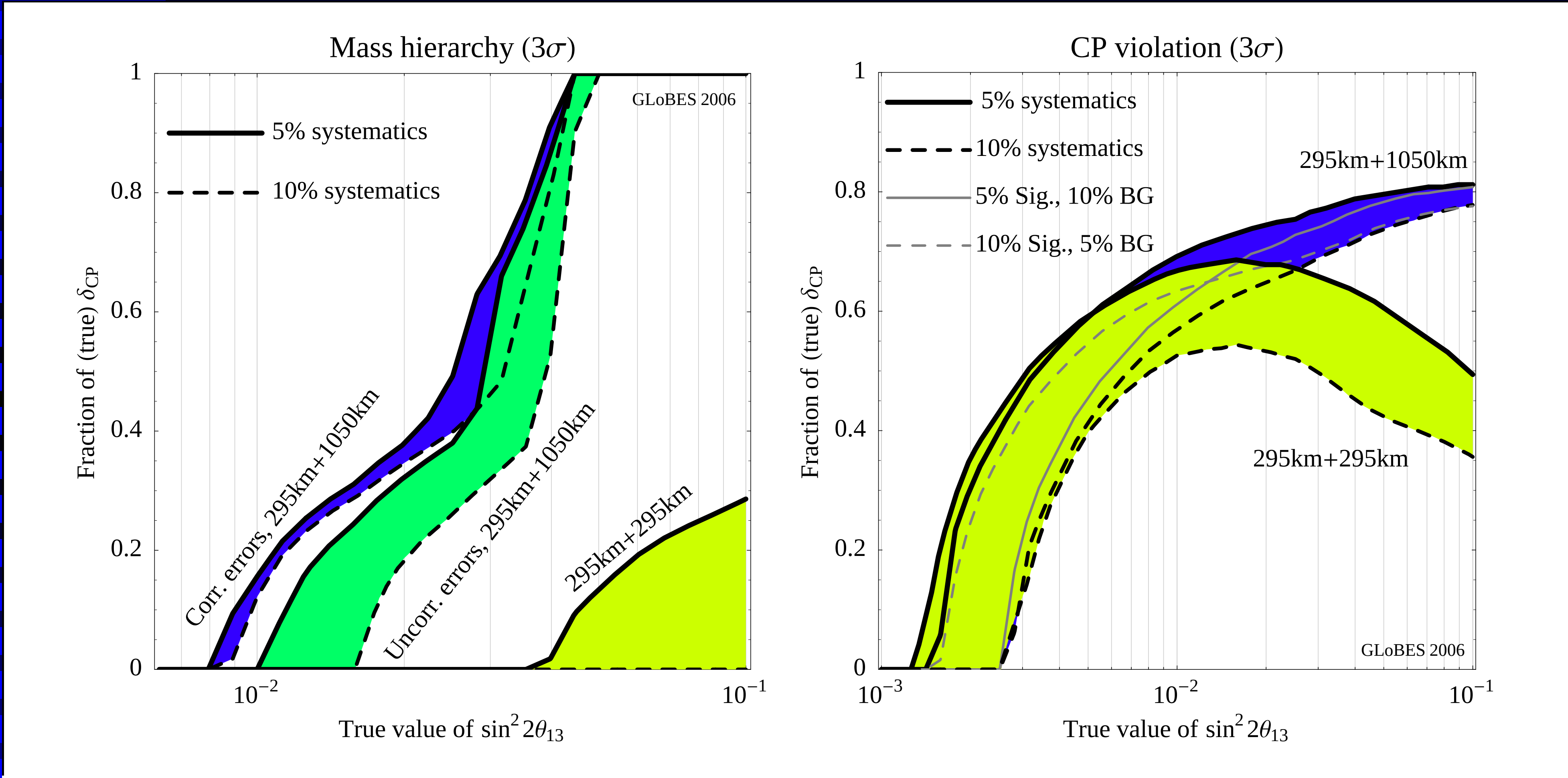
T2KK

- $4\,\mathrm{MW}$ protons from Tokai (JAERI)
- decay pipe fixed (same as for T2K)
- 2(!) water Cherenkov (WC) detectors with $m_{\mathrm{fiducial}} = 270\,\mathrm{kt}$
- 2 baselines $L_1 = 295\,\mathrm{km}$ and $L_2 = 1050\,\mathrm{km}$
- same off-axis angle of 2°
- 4 years ν and 4 years $\bar{\nu}$
- performance as in T2K
- π^0 rejection as in T2K

M. Ishitsuka *et al.*, PRD **72** 033003 (2005).
K. Hagiwara *et al.*, PLB **637** 266 (2006).

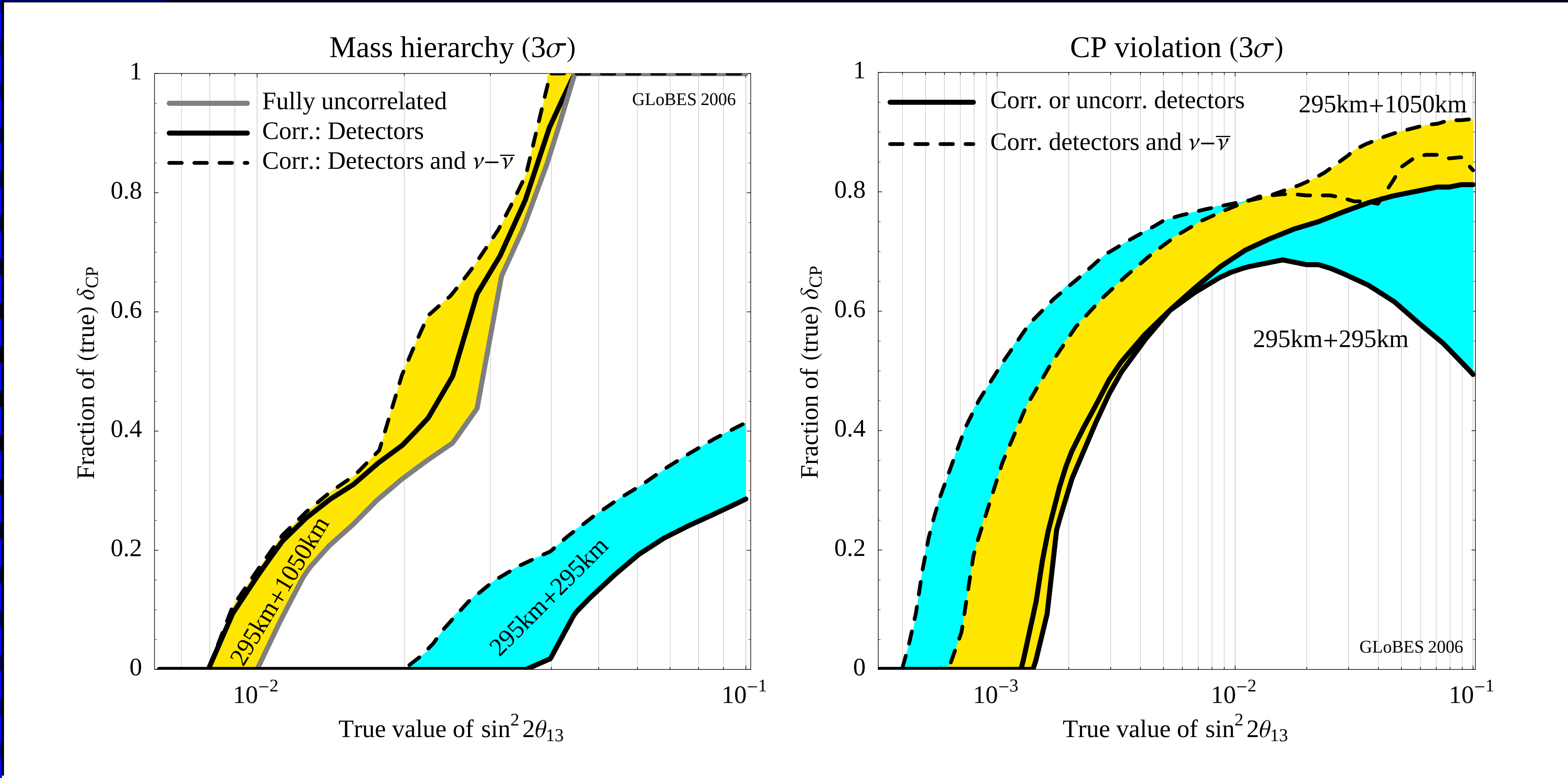
T. Kajita *et al.*, hep-ph/0609286.

T2KK



- second baseline crucial for mass hierarchy
- also helps CPV at large θ_{13}

T2KK



- detectors errors for mass hierarchy important
- for CPV one needs to reduce the $\nu/\bar{\nu}$ errors

Upgrades of NOνA

- $1.13\,\mathrm{MW}$ from Main Injector at Fermilab (corresponding to 10^{10} pot in $1.7 \times 10^{7}\,\mathrm{s}$ at 120 GeV)
- decay pipe fixed (same as for MINOS and NOνA)
- $100\,\mathrm{kt}$ liquid Argon time projection chamber (LArTPC)
- 3 years ν and 3 years $\bar{\nu}$ of $25\,\mathrm{kt}$ (TASD) NOνA at Ash River
- plus 3 years ν and 3 years $\bar{\nu}$ of both

Liquid Argon

Any upgrade of NOνA needs a detector that

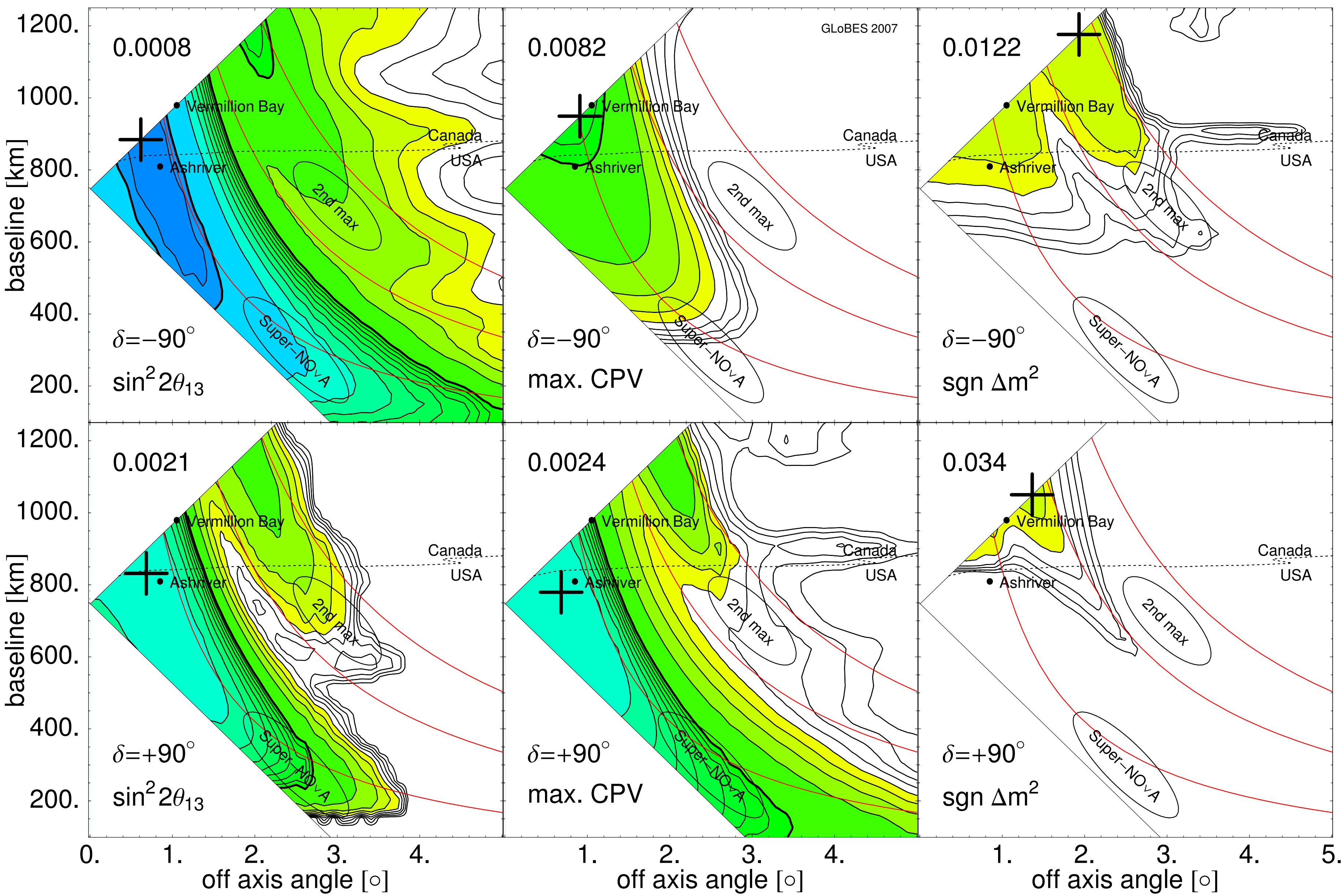
- delivers high statistics
- has very low NC backgrounds
- works on surface (or close to it)

Liquid Argon

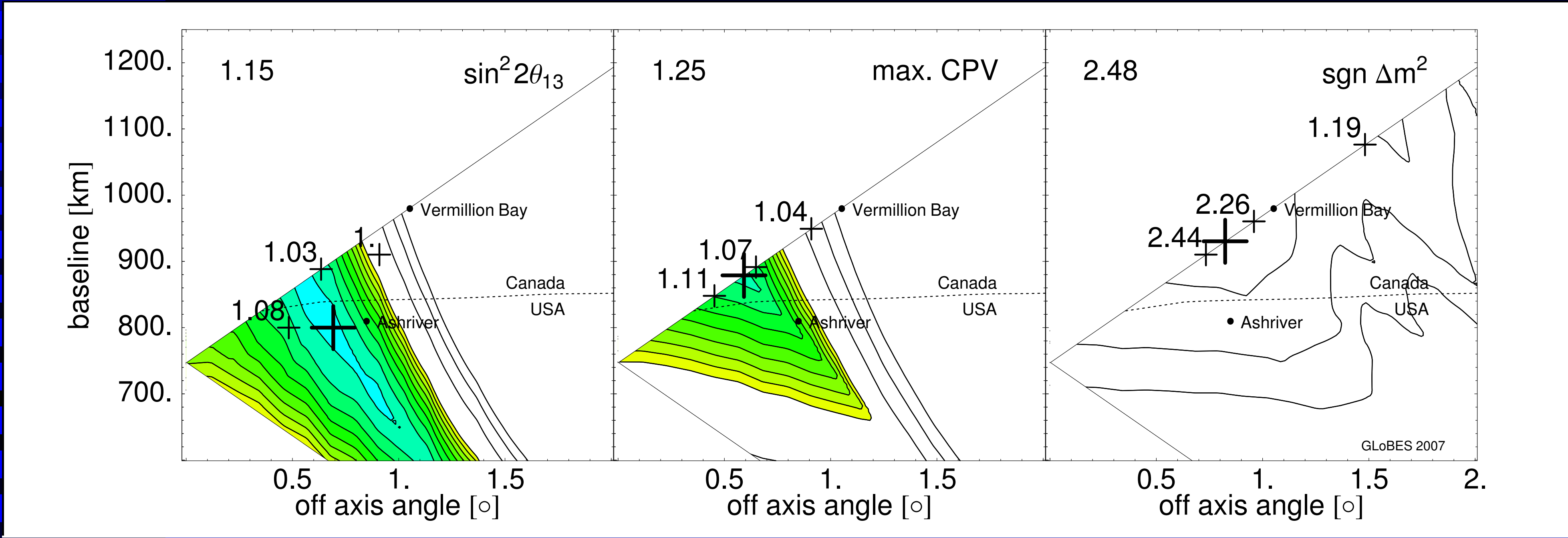
- 80% efficiency
- 0 NC background
- 5% energy resolution for QE events
- 20% energy resolution for non-QE events

B. Fleming, private communication

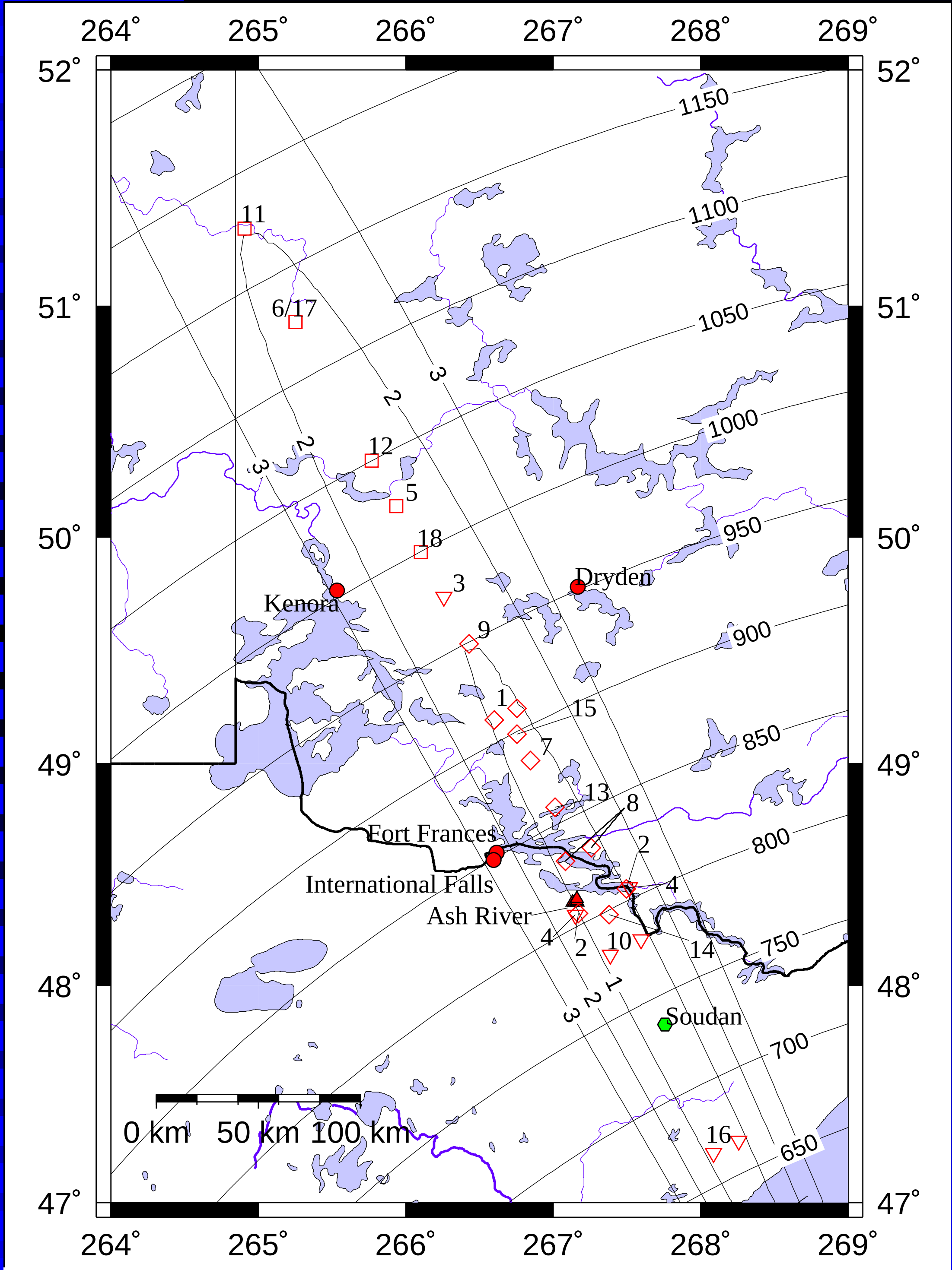
Where to put NOνA*



Is that location robust?

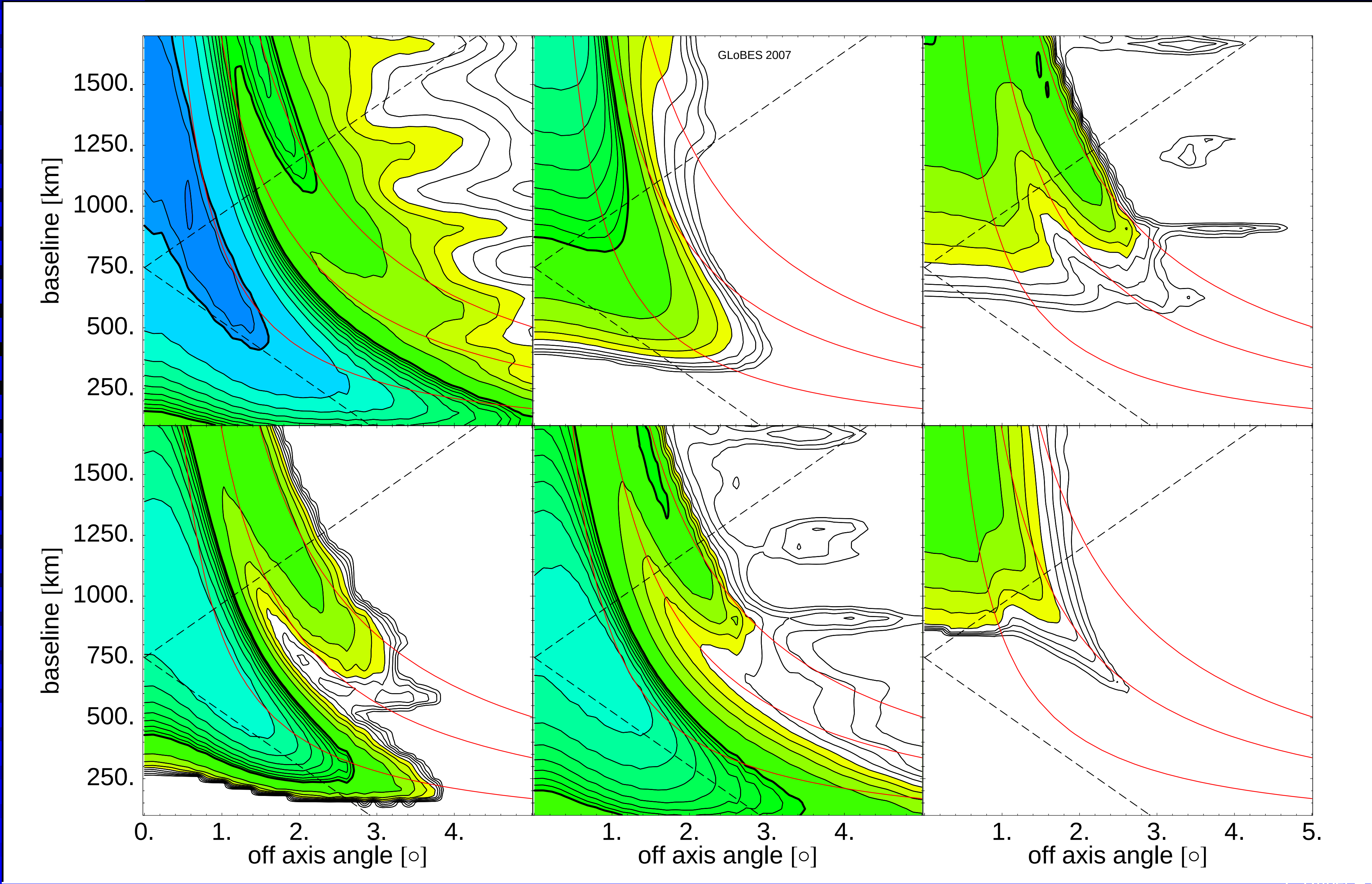


- optimal location in most cases in Canada
- uncertainty of Δm^2_{31} not a major problem
- not knowing δ is



Within the US, Ash River is as good as it gets!
We call that setup, *i.e.* a LArTPC with 100 kt at Ash River, NOνA*

On vs off-axis

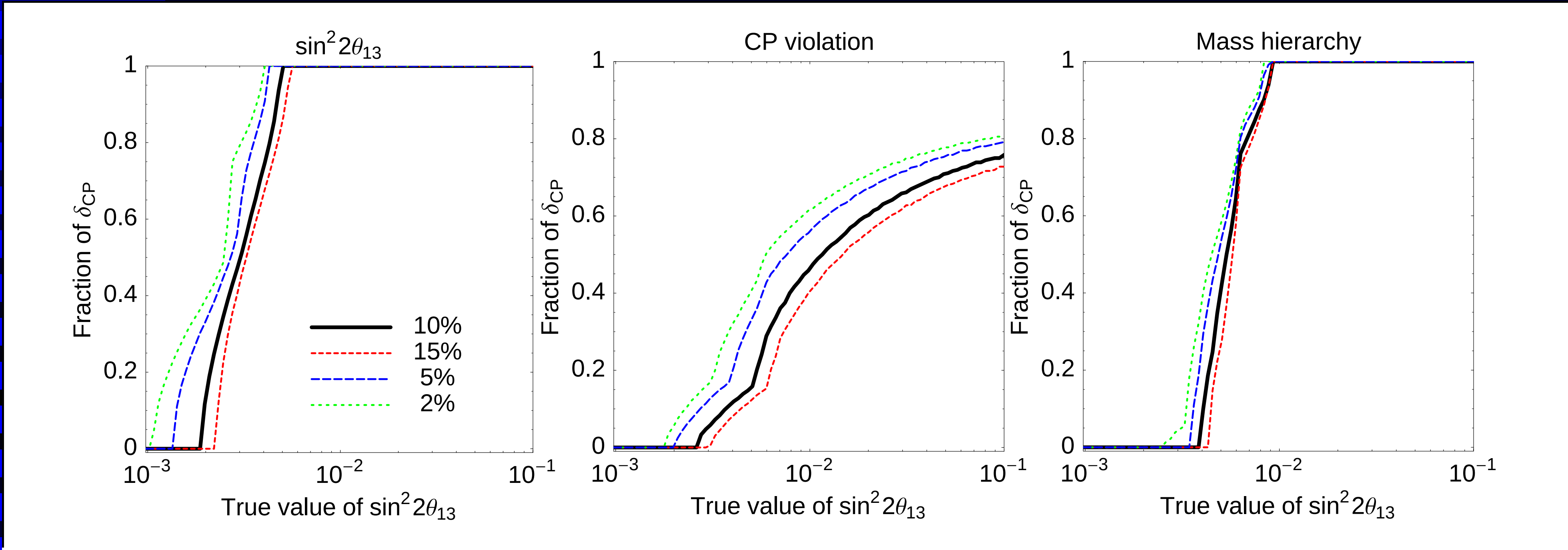


WBB

aka 'the BNL proposal' – originally proposed to be hosted by BNL, using $28\,\mathrm{GeV}$ protons from the AGS.

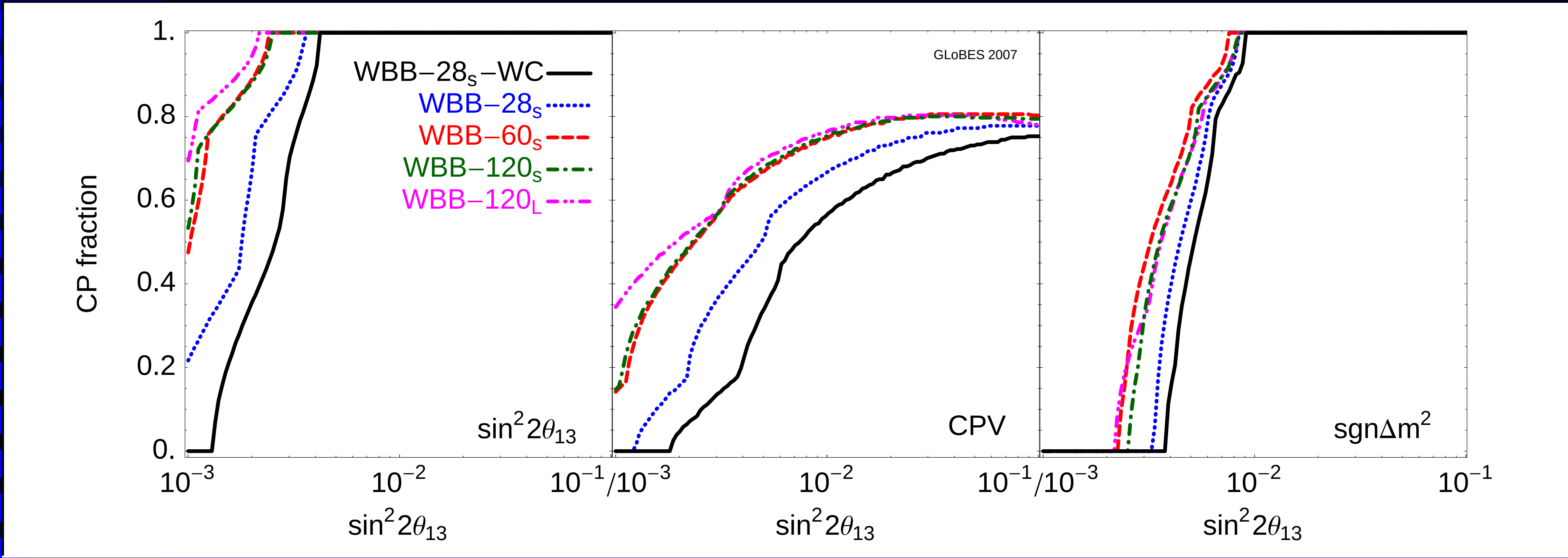
- 1 (ν) or 2 ($\bar{\nu}$) MW at 28 GeV
- 300 kt Water Cherenkov detector
- baseline of 1300 km, on-axis
- 5 years ν and 5 years $\bar{\nu}$
- performance based on full detector MC
  C. Yanagisawa
- improved π^0 rejection

WBB



V. Barger , M. Dierckxsens, M. Diwan, PH, C. Lewis, D. Marfatia, B. Viren, Phys.Rev.D74:073004,2006.

Proton energies



- WC data only available for $28\,\mathrm{GeV}$ protons
- all other lines use a 100 kt LArTPC
- comparison at $28\,\mathrm{GeV}$ yields a 4:1 mass ratio of water to Argon

Exposure

Everyone has different assumptions about

- seconds in a year
- number of years
- detector size
- beam power (or pot)

Therefore we introduce the concept of exposure

$$\mathrm{detector\,mass}\,[\mathrm{Mt}] \times \mathrm{target\,power}\,[\mathrm{MW}] \times \mathrm{running\,time}\,[10^7\,\mathrm{s}]\,.$$

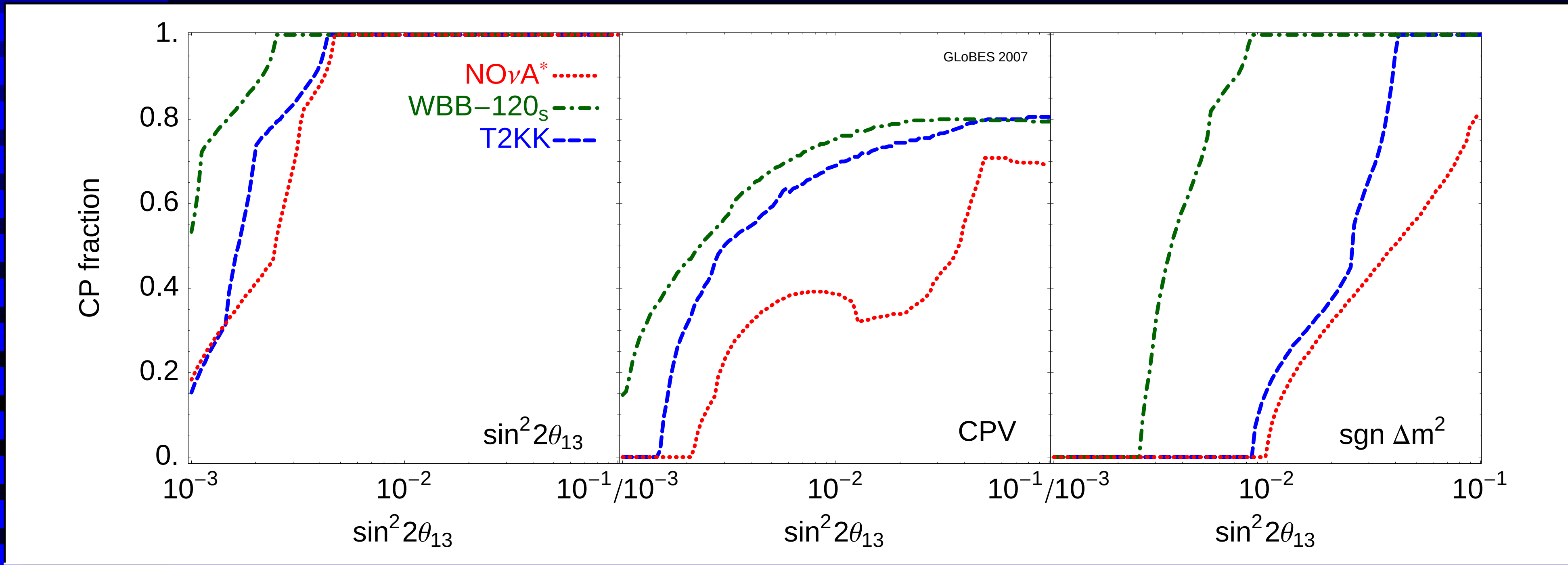
Clearly, the event rate is directly proportional to the exposure.

Setups

Setup	t_ν [yr]	$t_{\bar\nu}$ [yr]	P_{Target} [MW]	L [km]	Detector technology	m_{Det} [kt]	$\mathcal{L}$
NOνA*	3	3	1.13 ($\nu/\bar\nu$)	810	Liquid Argon TPC	100	1.15
$\mathrm{WBB}-120_{\mathrm{S}}$	5	5	1 (ν) +2($\bar\nu$)	1290	Liquid Argon TPC	100	2.55
T2KK	4	4	4 ($\nu/\bar\nu$)	295+1050	Water Cherenkov	270+270	17.28
β-beam	4	4	n/a	730	Water Cherenkov	500	n/a
NuFact	4	4	4 ($\nu/\bar\nu$)	3000+7500	Magn. iron calor.	50+50	n/a

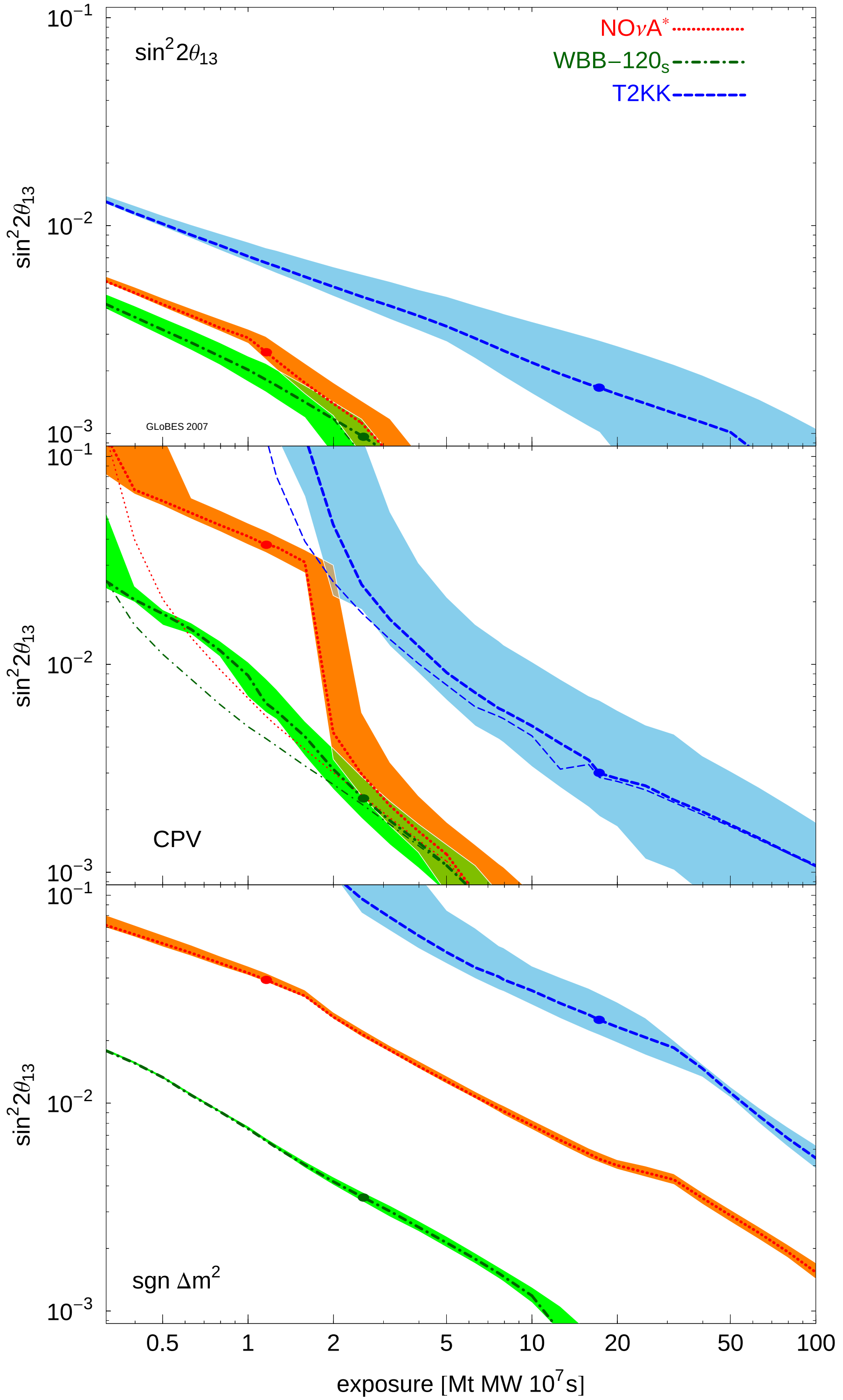
- 5% systematics for all setups
- Attention: from here on, also the WBB has a $100\,\mathrm{kt}$ LArTPC!

Comparison



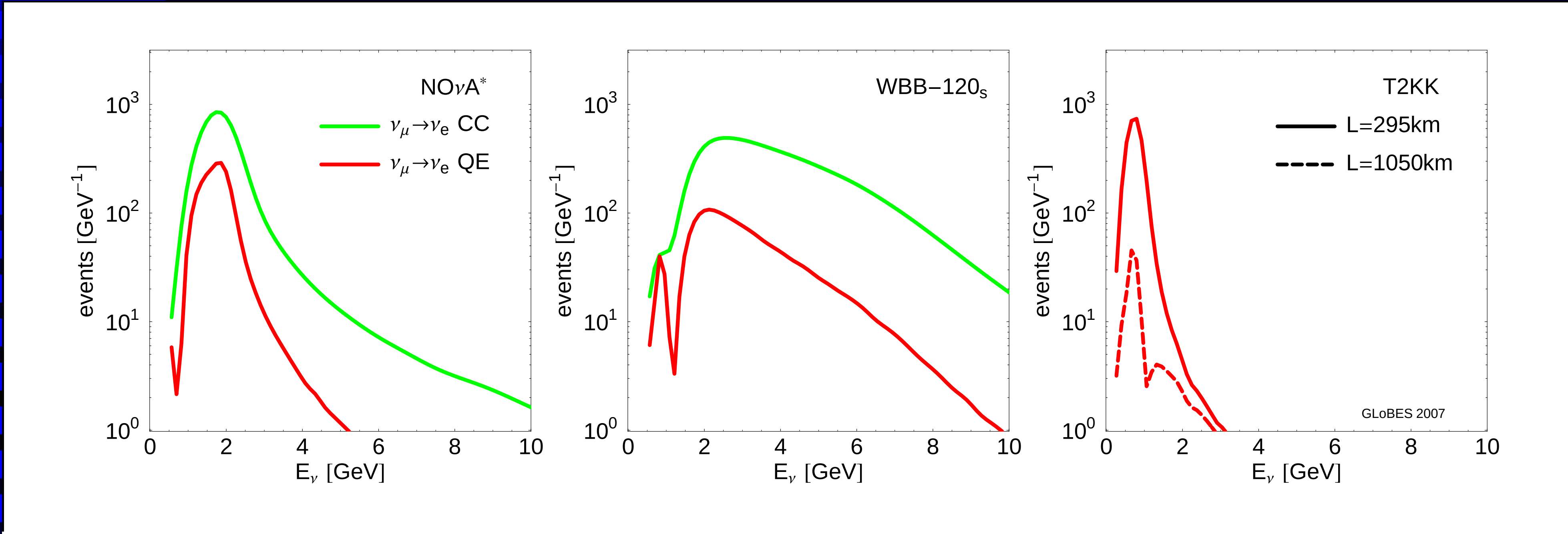
At nominal exposure

- WBB – 120_S best performance
- T2KK close for CPV



- T2KK needs by far the largest exposure
- NOνA* does well for θ_{13} and CPV if the exposure is large enough $> 2\mathrm{Mt}\,\mathrm{MW}\,10^7\mathrm{s}$ to resolve the $\mathrm{sgn}\Delta m$ degeneracy
- WBB-120_S performs best for any given exposure

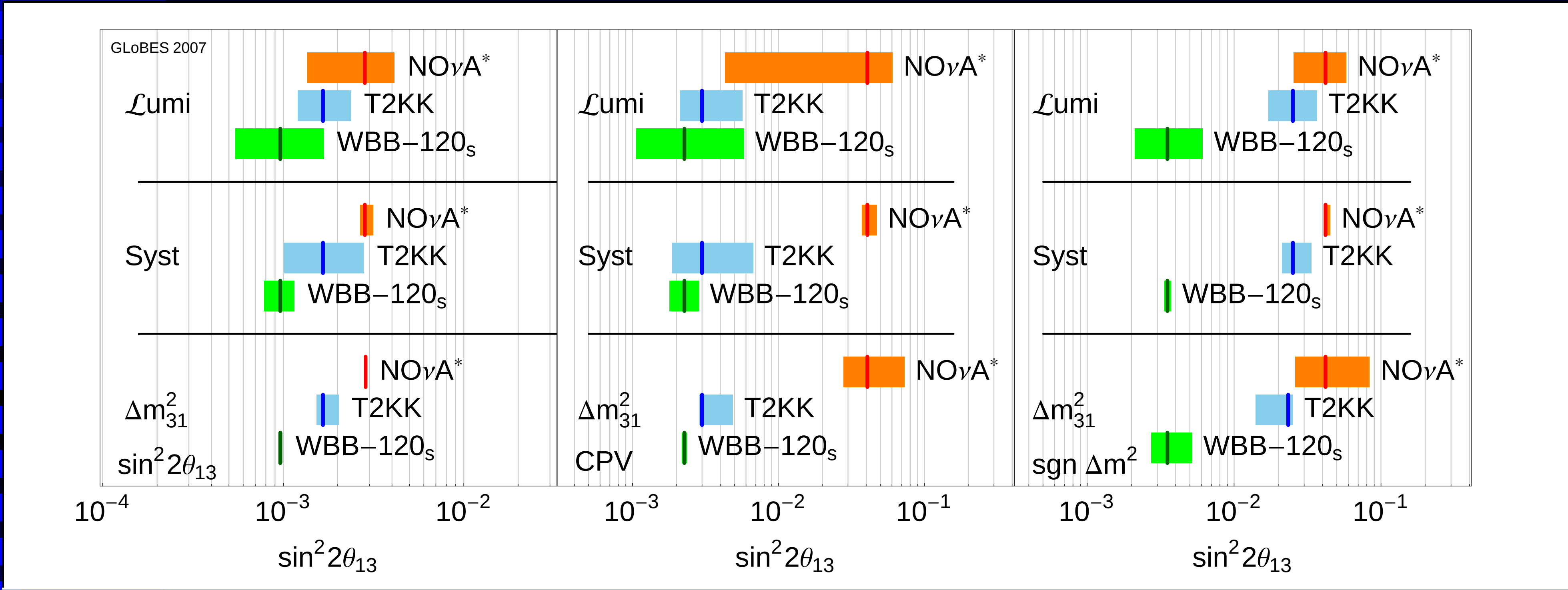
Event rates



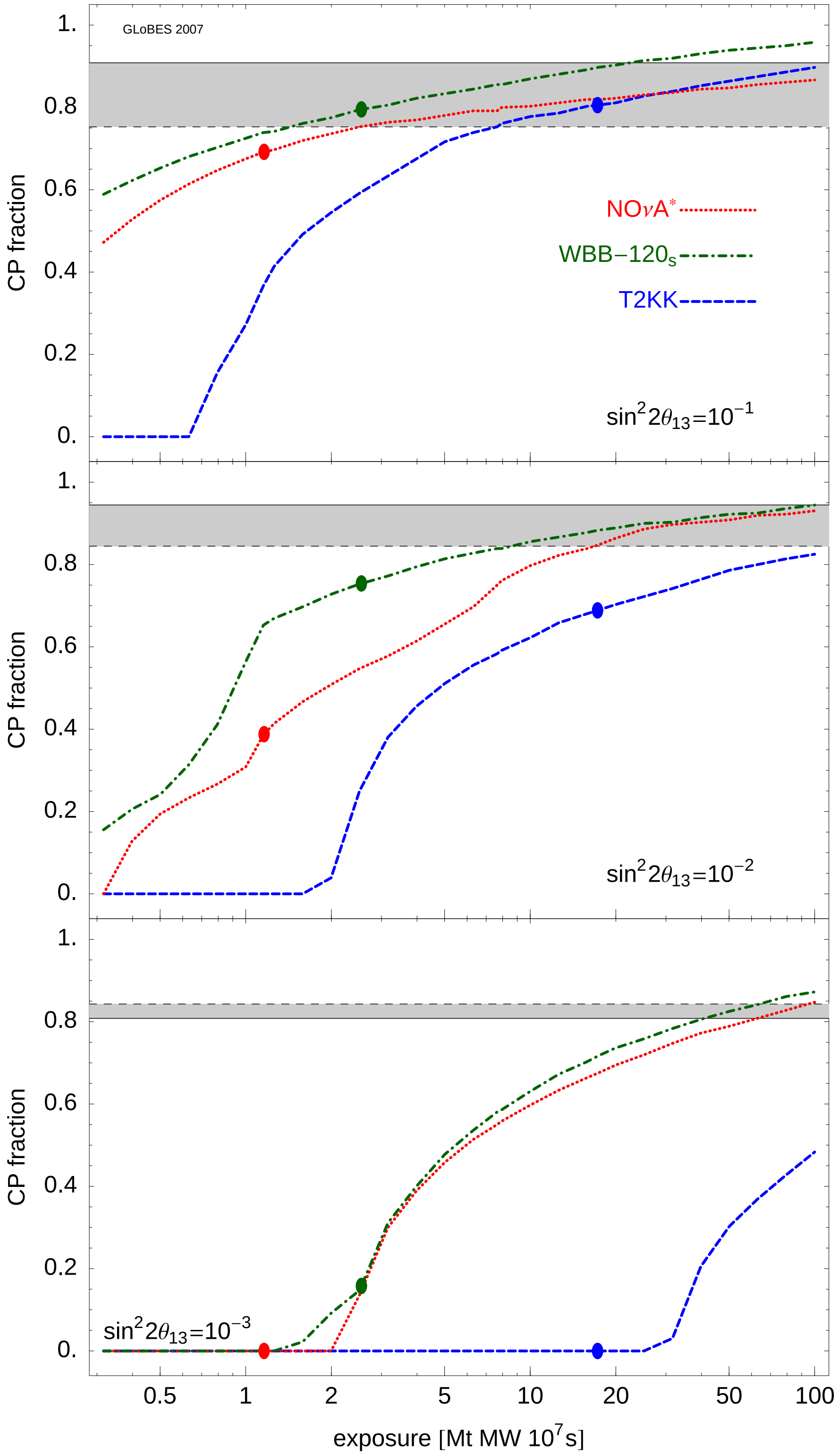
at $1\mathrm{Mt}\ \mathrm{MW}\ 10^7$s for $\sin^2 2\theta_{13} = 0.04$

- T2KK suffers from low statistics in the far detector
- NOνA* has a healthy event rate, but the baseline is too short

Robustness



- Exposure from 2 to 0.5 times nominal value
- Systematics from 2% to 10%
- Δm^2_{31} from $2.0 - 3.0\ \times 10^{-3}\,\mathrm{eV}^2$



At large θ_{13} any of the three setups can have the same performance as a NuFact or β-beam.

These large values would be certainly discovered by Double Chooz, Daya Bay, T2K and NOνA!

$\Rightarrow$ decision on next generation facility should wait at least for the first reactor data

Summary

- for $\sin^2 2\theta_{13} > 0.01$ no need for a neutrino factory or β-beam
- Exposure is the key factor – money and physics
- Detector technology plays a big role
- Off vs On-axis decision requires careful analysis
- NOνA* can be a competitive experiment
- Short distances ($< 500\,\mathrm{km}$) are disfavored
- Every strategy requires MW beams, 0.1 Mt detectors, 10 years of running

$\boxed{\text{500,000,000 \$\$}}$

Conclusion

For Fermilab this boils down to

- re-use the NuMI beamline and go via NOνA to a large liquid Argon TPC
- build a new beamline towards DUSEL (Homestake) and use a modular water Cherenkov detector

Both options would benefit from more protons.